Long Timescale Variability of AGN with *RXTE*

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Abstract. In this paper we review the very large contribution made by RXTE to our understanding of Active Galaxies (AGN). We discuss the relationship between AGN and Galactic Black Hole X-ray binary systems (GBHs) and show, by comparison of their powerspectral densities (PSDs) that some AGN are the equivalent of GBHs in their 'high' state, rather than in their 'low' state as has previously been assumed. We plot the timescale at which the PSD slope steepens from -1 to -2 against the black hole mass for a sample of AGN, and for Cyg X-1 in its high and low states. We find it is not possible to fit all AGN to the same linear scaling of break timescale with black hole mass. However broad line AGN are consistent with a linear scaling of break timescale with mass from Cyg X-1 in its low state and NLS1 galaxies scale better with Cyg X-1 in its high state, although there is an exception, NGC3227. We suggest that the relationship between black hole mass and break timescale is a function of another underlying parameter which may be accretion rate or black hole spin or, probably, both. We examine X-ray spectral variability and show how simple 'flux-flux' plots can distinguish between 'two-component' and 'spectral pivoting' models. We also examine the relationship between the X-ray emission and that in other wavebands. In the case of X-ray/optical variability we show how cooler discs in AGN with larger mass black holes lead to greater proximity of the X-ray and optical emission regions and hence to more highly correlated variability. The very large amplitude of optical variability then rules out reprocessing as the origin of the optical emission. We show how the radio emission in NGC 4051 is strongly correlated with the X-ray emission, implying some contribution to the X-ray emission from a jet for which there is some evidence in radio images. We point out, however, that we have only studied in detail the X-ray variability of a handful of AGN. There is a strong requirement to extend such studies to unbiased samples of many hundreds of AGN and so a strong need for a very sensitive (<mCrab in a day), long lived (∼10 years) all sky monitor.

1. INTRODUCTION

Active Galaxies (AGN) typically have black holes which are factors of $> 10^6\times$ more massive than the $\sim 10 M_\odot$ black holes in galactic X-ray binary systems (GBHs). Thus, if timescales scale linearly with mass, we need to observe for a few years to address the same problems that can be addressed, in GBHs, in a few minutes of observation. As with GBHs, we also require well sampled lightcurves to study AGN. Problems of interest include the relationship between AGN and GBHs, the explanation of AGN X-ray spectral variability, and the relationship between the X-ray emission, and that in other bands, in AGN.

Prior to the launch of *RXTE* it was impossible to obtain the ∼daily observations, stretching over many years, that are required for the proper study of AGN. *RXTE* truly revolutionised the study of AGN by providing just such lightcurves. In this paper we will summarise some of the main results that have come from programmes which we, and other groups (eg [4]), have carried out with *RXTE*. The comparison between AGN and GBHs underlies much of this work and basic comparison of their X-ray variability properties, through the powerspectral density (PSD), will be discussed in Section 2. We will then (Section 3) investigate the reasons behind X-ray spectral variability in AGN and, in Section 4, we will discuss the relationship between the X-ray and optical variability of AGN, a subject about which there has been much confusion. In Section 5 we will discuss the relationship between the X-ray and radio variability of (non-beamed) AGN. We will conclude (Section 6) with a discussion of where the study of AGN X-ray variability should go next, and what new X-ray observational capabilities we require to make progress.

2. COMPARISON OF AGN WITH GALACTIC BLACK HOLE X-RAY BINARY SYSTEMS

Case Example: NGC 4051

The relationship between AGN and GBHs is currently one of the hot topics in high energy astrophysics, and is one in which *RXTE* has been crucial to improving our understanding.

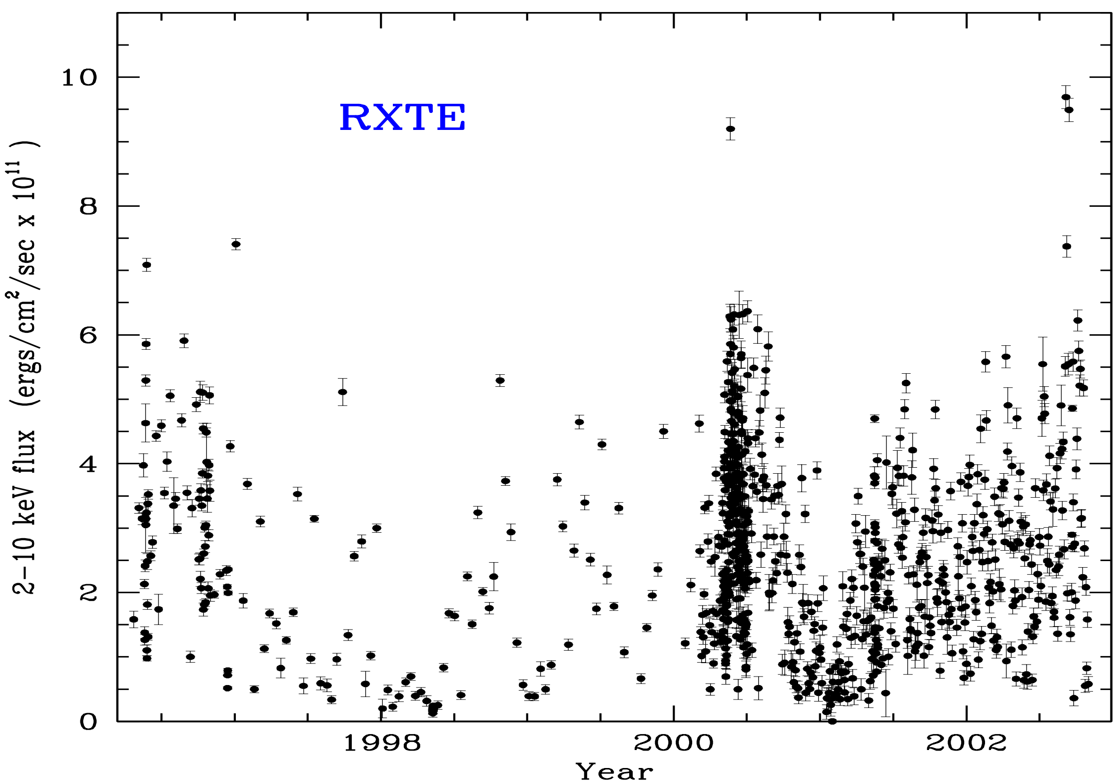

FIGURE 1. *RXTE* Long Term 2-10 keV lightcurve of NGC 4051. Each data point represents an observation of $\sim$ 1 ks.

Observations with EXOSAT, coupled with some archival data, indicated a possible similarity between the PSDs of AGN and GBHs [16]. Both types of PSD are steep at high frequencies and flatten, below a break or 'knee' frequency. GBHs, however, are found in at least two states: the low flux, hard spectrum ('low') state and the high flux, soft spectrum ('high') state [15, 19, 2]. The PSDs of these two states are different. At high frequencies both PSDs have slopes of ~ -2.5 (plotting log of power against log of frequency). Below a break frequency ($\nu_B \sim 3$ Hz for the low state and ~ 15 Hz for the high state) the PSDs both flatten to a slope of -1. In the high state there is no other observable slope change but in the low state the PSD flattens further (below $\nu \sim 0.3$Hz) to a slope of zero. It has usually been thought, based on the similarity of their energy spectra, that AGN are the analogues of GBHs in their low state.

Early indications were that the break timescale scaled with black hole mass [16, 20] but the long timescale (weeks - years) X-ray lightcurves of AGN were not of adequate quality to properly determine the break timescales. However since the launch of the Rossi X-ray Timing Explorer (*RXTE*, [24]) in December 1995 we have been able to obtain excellent long timescale AGN lightcurves, such as that shown here (Fig 1) of NGC4051 (from [18]). The observations shown here were made with the Proportional Counter Array (PCA) [34] on *RXTE* which, for typical AGN, has useful sensitivity in the range 2-20 keV. A good measurement of the flux can be obtained in $\sim$ 1ksec and the unique rapid slewing capability of *RXTE* allows for many such observations to be made in a day. Without the rapid slew capability, it would not have been possible to produce lightcurves such as that shown in Fig 1.

In Fig 2 we show the PSD which is derived from the above lightcurve. Here we combine the *RXTE* observations with a 120ksec continuous observation from *XMM-Newton* which samples the higher frequencies. Due to the non-continuous nature of the *RXTE* lightcurves we have developed a simulation-based modelling method [29] to determine the shape of the PSD. Here we unfold the observed PSD from the best fit model in order to give the best representation that we can of the true PSD. This PSD is the best yet produced for an AGN. [Note that here we plot log(frequency times power) vs log(frequency) so that a slope of zero, ie the equivalent of a slope of -1 if we had plotted log(power) vs log(frequency), would indicate equal power in equal decades of frequency. The

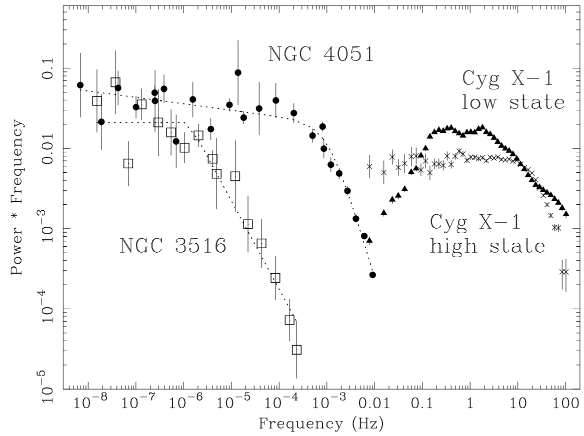

FIGURE 2. Unfolded PSDs of NGC 4051 (filled circles), NGC 3516 (open squares) and Cyg X-1 in its low (filled triangles) and high (asterisks) state.

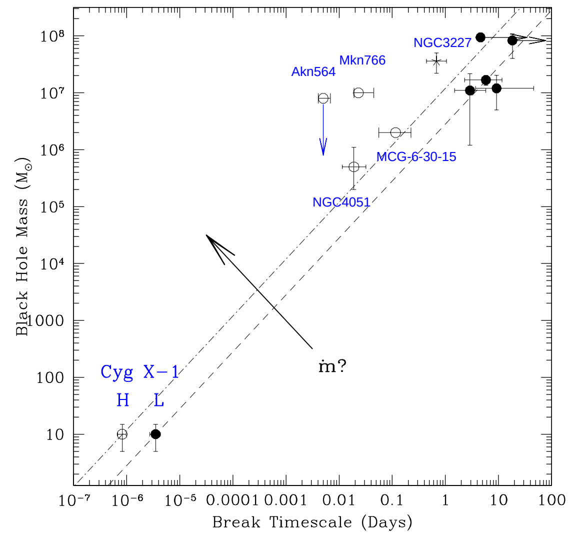

FIGURE 3. Summary of PSD break timescales, from slope -2 to -1, for AGN of various black hole masses. NLS1s are shown as open circles and broad line Seyferts are shown as filled circles. The high-soft (H) and low-hard (L) states of Cyg X-1 are also plotted and lines (dot-dash and long-dash respectively) of slope 1.0 are drawn through those points. The solid arrow labelled with $\dot{m}$ indicates the way that the break timescale/mass line may move with increasing accretion rate. All break timescales refer to a break where the PSD slope below the break frequency is ~ -1. All break timescales are derived on the basis of a sharply broken powerlaw model.

frequency times power representation gives a better idea of the frequencies at which most of the variability power lies.]

A break in the PSD of NGC4051 is clearly visible. For comparison we show the PSDs of Cyg X-1 in both the low and high states. We can clearly see that the PSD of NGC4051 is the same shape as that of Cyg X-1 in its high state. If the break timescales scale linearly with mass, we imply a black hole mass of $\sim 3^{+2}_{-1} \times 10^5 M_\odot$, which compares very well with the mass determined recently from reverberation mapping of $\sim 5^{+6}_{-3} \times 10^5 M_\odot$ [22]. This PSD provides the first definite confirmation of an AGN as a high state object. *RXTE* was crucial in showing that the PSD continues with a flat slope for many decades below the break frequency, and does not show the second break seen in Cyg X-1 in the low state.

PSD Break Timescale and Black Hole Mass

In Fig 2 we also show the PSD of NGC3516 made from *RXTE* observations. A version of this PSD has previously been shown by Edelson and Nandra [4] but here we show the version derived by means of our modelling. We can see a break in the PSD of NGC3516, and we note that the break is at a lower frequency than the one in NGC4051. However we do not have sufficient coverage of the PSD below the break to determine whether NGC3516 is a high or low state system. However NGC3516 has a higher black hole mass than NGC4051, which is at least consistent with a scaling of break timescale with black hole mass.

There are now enough break timescales in the literature that it is possible to plot break timescale against black hole mass to test the linear scaling hypothesis and Markowitz et al. [14] have made such a plot, combining *RXTE* with *XMM-Newton* and *Chandra* observations. We [18] have also made such a plot, with the slight difference from Markowitz et al. that we plot only the timescale at which the PSD (in power units) steepens from a slope of ~ -1 to a slope of ~ -2 (Fig 3) and do not include any timescales associated with breaks from slope of -1 to 0. In high state systems the break from slope -2 to -1 is the only break in the PSD but in low state systems it is the higher of the two breaks. In most AGN we do not, however, know which break it is. We plot narrow line Seyfert 1 galaxies (NLS1s) with open circles and broad line Seyferts with solid circles. We also plot, in Fig 3, the break timescales for Cyg X-1 in both its high and low states. The best fit line to all of the AGN data (not shown) does not pass through either of the Cyg X-1 points. We also draw lines representing linear scaling of black hole mass with break timescale and place one line separately through the high and low states of Cyg X-1. Note that these lines are not fits. However the NLS1s are more consistent with linear scaling from the high state of Cyg X-1 and the broad line AGN are more consistent with scaling from the low state. There is, of course, an exception in that NGC3227 (paper in preparation), which is a broad line AGN, is more consistent with scaling with the high state.

So what is going on? We propose that the relationship between break timescale and black hole mass is not the same for all AGN. We propose that there is (at least) one other underlying parameter which governs the location of the break timescale/mass relationship so that it may be different for galaxies of different type. To first order Fig 3 shows that, for a given black hole mass, the break timescale is smaller in NLS1s. The supposition that break timescales, for a given mass, are shorter in NLS1s is strongly supported by the observations of Leighly [11] who shows that the rms variability of NLS1s is greater than that of broad line galaxies. This result is easily explained if the PSD break frequencies are lower in broad line galaxies than in NLS1s and so broad line galaxies contain less variability power arising at high frequencies.

What is the parameter underlying the location of the break timescale/mass relationship? Before we discuss what that parameter might be, we must first consider the origin of the break timescale. In NGC4051 the break timescale is approximately what one would expect for the viscous timescale at a few gravitational radii (eg [26]), ie the inner edge of the accretion disc. In galactic systems it is generally believed (eg [6, 15, 8]) that the inner edge of the accretion disc moves closer to the black hole as a system changes from the low to the high state. If the break timescale is associated with the edge of the accretion disc, and the same physics (eg viscosity) defines the characteristic timescale in all black hole systems, then movement of the edge of the disc provides a natural explanation of Fig. 3. The main question then would be, what parameter affects the location of the inner edge of the disc? An obvious possibility would be the accretion rate, $\dot{m}$ (eg [15]). NLS1s are generally thought to be radiating at higher luminosities (relative to the Eddington luminosity) than broad line galaxies, which is consistent with the suggestion that $\dot{m}$ is a crucial parameter.

Alternatively, if the discs in all AGN reach right down to the last stable orbit, then we have to alter the location of the last stable orbit and the last stable orbit is closer in for black holes of higher spin (cf [32]). Thus although it is not possible, on the timescales on which changes are seen, to alter the spin of an individual GBH (or AGN) in order to change it from a low to a high state system, it is possible that, for an ensemble of AGN, a range of spins might provide for a distribution in the mass/break-timescale plane. The location of NGC3227 above the high state line implies that accretion rate cannot be the only factor affecting the mass/break timescale relationship and so spin may well be important too.

X-Ray 'Off' States

One of the surprises to come from our *RXTE* AGN monitoring programme has been the detection of so-called 'off' states, where the X-ray flux from NGC4051 becomes extremely low for periods of a few months. The most prominent off-state was seen in spring 1998 [28]. The off states have been very important for our understanding of AGN X-ray variability. They cannot be explained if the X-ray variations come from random shots. Simulations show that we would never achieve the observed extended periods of very low flux with random shots. We are able to explain the off-states in terms of a link between the variations on long timescale and those on short timescales. When the amplitude of the long period variations becomes low, the amplitude of the short period variations also becomes low, so that the total flux remains low. This relationship is characterised by the 'rms-flux' relationship [27] where we see that the rms variability of both GHBs and AGN is proportional to the flux. Thus again we see a close link between the behaviour of AGN and GBHs.

The rms-flux relationship finds a ready physical explanation in terms of the annular model of Lyubarskii [12] where a specific timescale is associated with each annulus of an accretion disc, with shorter timescales being associated with the annuli closer to the black hole. Perturbations, perhaps due to variations in accretion rate, propagate inwards and, in order to explain the rms-flux relationship, we propose that the amplitude of variability from each annulus depends on the amplitude of variations propagating in to that annulus.

The link between variations of different period immediately leads to the prediction of non-linear variability which we will discuss elsewhere.

3. X-RAY SPECTRAL VARIABILITY

For many years it has been known that the X-ray spectral indices of (non-beamed) AGN become steeper as the flux increases (eg [9, 10]). Based on our early *RXTE* observations [17] we suggested that the spectral steepening might be the result of combining a constant flux, hard spectrum, component with a varying flux, steep spectrum, component. A similar scenario was later proposed by Shih et al [23]. Recently we have considerably simplified the process of studying spectral variability [25]. We simply plot the flux in one spectral band against the flux in a different band (so called 'flux-flux plots'). If variability is due to the two-component model discussed above, we will see a simple linear relationship between the fluxes in the two bands, as in MCG-6-30-15 (Fig 4). If, on the other hand, the observed variability

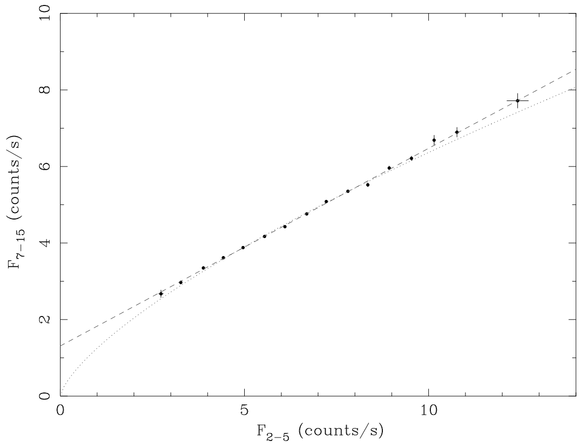

FIGURE 4. Flux-flux plot for MCG-6-30-15. The dashed line represents the best-fit two component model and the dotted line represents spectral pivoting of the dominant emission component. In this case the two component model is the best fit to the data.

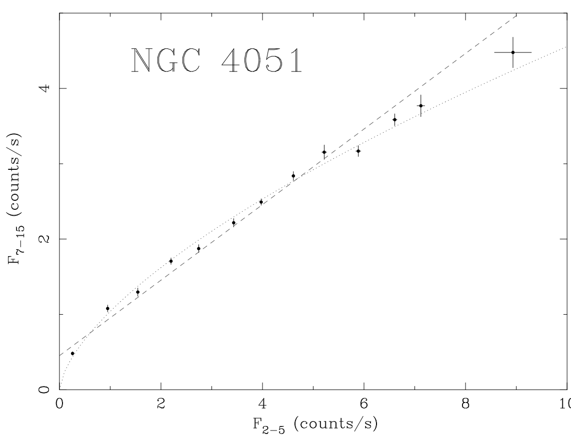

FIGURE 5. Flux-flux plot for NGC4051. The dotted and dashed lines are as described in Fig 4. In this case spectral pivoting is the best description of the data.

arises from intrinsic spectral variability of the dominant emission component, there will be a curved or non-linear relationship between the fluxes in the two bands. In the case where the spectrum pivots about some high energy ∼few hundred keV, (eg [33]) there will be a powerlaw relationship between the fluxes in the two bands. Such a relationship is a good fi t to the observations of NGC4051 (Fig 5).

The offset on the hard band flux axis, when the soft flux approaches zero, gives an indication of the flux in the constant hard spectrum component, in the particular hard band. By plotting the flux in a variety of hard bands against the same soft band we are therefore able to build up a spectrum of the constant hard component. We have shown [25] that the constant component, at least in the case of MCG-6-30-15, has the shape of a reflection spectrum. However the strength of this reflection component is greater than would be expected for a reflector fi lling half of the sky, as seen from the X-ray source. Fabian and Vaughan [7] have proposed that, in such cases, reflection may be boosted by light bending effects close to a spinning massive black hole which turn additional light back onto the accretion disc.

4. X-RAY/OPTICAL VARIABILITY

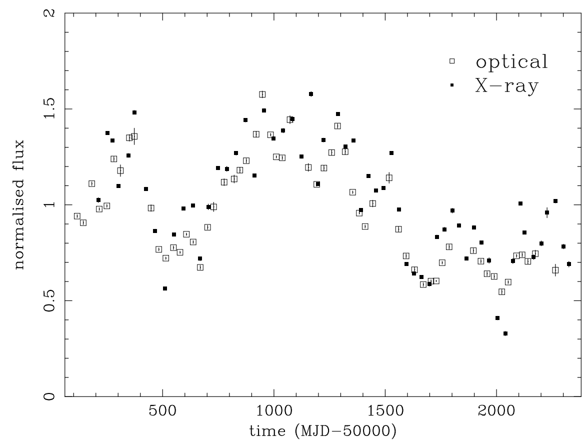

FIGURE 6. X-ray (filled squares) and optical continuum at 5100Å (open squares) lightcurves for NGC5548. Both lightcurves have been normalised to their respective means.

The relationship between X-ray and optical variability in (non-beamed) AGN has, until recently, been confused. Despite many observations (eg [13, 5, 21]), no convincing X-ray/optical correlation had been obtained. However we have recently demonstrated a strong correlation between the X-ray (with *RXTE*) and optical variations in NGC5548 [30]. In Fig 6 we show the X-ray and optical variations in NGC5548 superposed, with the variations in each band normalised to the mean flux in that band. We note that the variations are very strongly correlated and, moreover, the amplitude of variations in the optical band is, if anything, greater than in the X-ray band. Such a large amplitude of optical variation cannot be explained if the optical emission arises as a result of reprocessing of the X-ray emission as then we would expect a much lower relative amplitude of variability.

So why were we successful in detecting strongly correlated X-ray/optical variations, and what is the mechanism driving the optical variations?

Our hypothesis is that the reason behind the large optical variation in NGC5548 is the large black hole mass in NGC5548 ($\sim 10^8 M_\odot$), compared to the smaller black hole masses in the AGN studied previously. The accretion disc is cooler around a more massive black

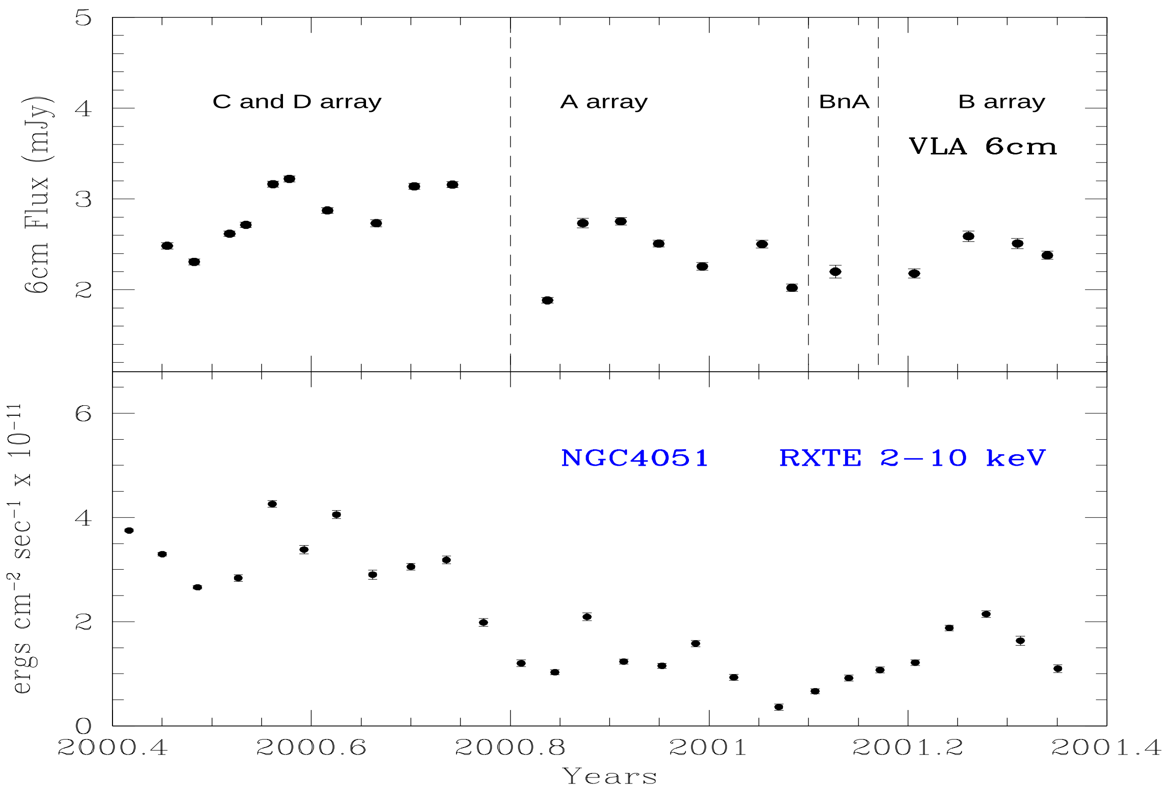

FIGURE 7. Radio and X-ray lightcurves of NGC4051. The radio observations were made with the VLA at 6cms. The observations were made is all four array configurations (A, B, C, D). As we move from A to D configuration, the VLA becomes sensitive to larger scale structure. We have made our best attempt to remove the flux of the larger scale structure from our observations, leaving only the flux of the compact core. We have binned up the X-ray observations, from *RXTE*, to the same time resolution as the radio observations.

hole and so the region primarily responsible for the optical emission will lie closer (in terms of gravitational radii) to the central X-ray emitting region. E.g. we calculated that the optical emission region lies within $\sim 20R_G$ from the black hole in NGC5548 but within $\sim 100R_G$ in NGC3516($\sim 10^7 M_\odot$) [5, 13] and $\sim 340R_G$ in NGC4051($\sim 3\times 10^5 M_\odot$) [21] where, at best, only very weak correlated optical variations are seen. Thus whichever variations affect the X-ray emitting region, will also affect the optical emitting region in NGC5548. However for AGN where the X-ray and optical emitting regions are more separated, we can expect a reduced correlation.

5. X-RAY/RADIO VARIABILITY

We had previously shown [21] that, in the rms optical spectrum of NGC4051, the HeII 4686 line disappears when the source is in a very low flux state. However the Balmer lines remain. We proposed that the hotter inner part of the accretion disc, which would produce photons of sufficient energy to ionise helium, might become advective in low flux states. Di Matteo et al. [3] have proposed that radio emission should increase when the flow becomes advective and so we carried out parallel radio and X-ray observations of NGC4051 with the VLA and *RXTE* respectively. The results are shown in Fig 7. We can see that, rather than being anti-correlated, the radio and X-ray emission are positively correlated (Fig 8).

A strong positive correlation rules out the advective model but is consistent with at least some part of the X-ray emission (and most of the radio emission) coming from a jet. Indeed the radio maps do show jet-like structure in the nucleus of NGC4051 (Fig 9; see also [1]).

6. WHERE DO WE GO FROM HERE?

RXTE has revolutionised our understanding of AGN.

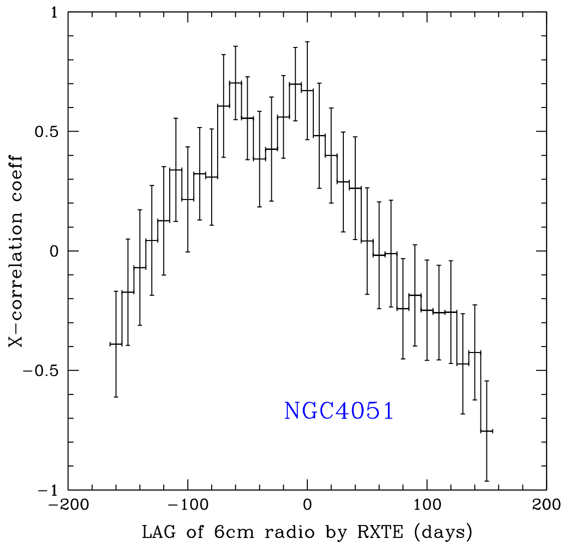

FIGURE 8. Cross-correlation of the lightcurves shown in Fig 7. The two lightcurves are well correlated with a lag close to zero days.

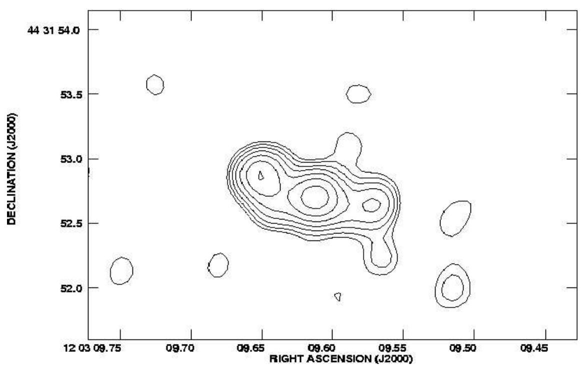

FIGURE 9. VLA A-configuration map of NGC4051 showing jet-like structure. The central component has a flat spectrum and the outer components have steep spectra. Note how the western component turns southwards. The B-configuration map, which shows larger scale structure, reveals extended emission pointing off from the western component shown here.

However so far we have only studied, in detail, the X-ray variability of a handful of AGN. Almost certainly our sample is biased and care must be taken in drawing too definite conclusions. There is an urgent need to extend X-ray variability studies to a large, and unbiased, sample of AGN. With regard to optical/X-ray variability, the advent of optical robotic telescopes such as the 2m Liverpool Telescope on La Palma mean that such studies are becoming much easier, as long as we can continue to provide X-ray monitoring. Hopefully *RXTE* will continue for many years but, in the future, the obvious and urgent need is for an X-ray all-sky monitor of high sensitivity and long lifetime. We briefly discuss, in order of priority, the required parameters of such a mission.

Critical Parameters for the next generation X-ray all-sky monitor

Sensitivity is the first priority. 0.5mCrab in one day (5σ) is necessary to properly detect 'off' states. Ideally the systematics should be well enough understood that we can integrate up for a few days to improve long term sensitivity. Sensitivity much worse than this level would mean that few AGN would be available for study. Sensitivity at this level would enable us to find low frequency QPOs if at the same strength as in galactic systems.

The mission duration must be long enough that we can measure the PSD for at least 2 decades, and preferably more, below the break from slope -2 to -1 (in power space) so that we can distinguish high from low state systems. As the black holes in most AGN are more massive than in NGC4051, we require durations of ~ 10 rather than ~ 2 years.

If we are content to study the few hundred known AGN with fluxes around the mCrab level, positional resolution need not be much better than that of the collimated *RXTE* PCA (which has a triangular response, of full width 1° at zero response) as few AGN are badly confused at the mCrab level. However to detect new AGN, and particularly X-ray events from AGN with optical counterparts fainter than about 16 mag, we require better positional resolution, at the few arcmin level.

We would like sufficient energy range, and resolution, to be able to distinguish variations in absorbing column from variations in intrinsic luminosity and to measure the spectral index. Coverage of the 0.1-20 keV band with proportional counter energy resolution ($\sim 20\%$) would suffice for most investigations. However that is still quite a stringent requirement and instrumentation realities would probably force a restriction of the band.

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